Integrality and Meaning: Essential and Orthogonal Dimensions Of Graphical Data Display

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There are few sound principles, rules, or laws to guide construction of graphic displays of medical data or information. The present paper describes two orthogonal dimensions of data displays: integrality and meaningfulness. These are hypothesized to be both fundamental building blocks of a theory of graphic representation and pragmatically useful principles for organizing previously created graphic displays and creating new ones. Examples taken from recent medical informatics literature illustrate high and low integral vs. high and low meaningful displays. If the present analysis is correct, then pattern recognition tasks will be better supported by displays that are high on both integrality and meaningfulness. Integrality, it is hypothesized, increases the degree to which a pattern is apparent. Meaningfulness increases the degree to which a pattern, once detected, is interpretable.

INTRODUCTION

Graphical display of information in medicine is an important domain but one that is poorly understood. There are occasional examples of excellent displays that make an apparently difficult problem easy to understand. Such displays elegantly summarize large amounts of data. They make the significant apparent. One historical example is Florence Nightingale's use of polar graphs (see Figure 2 below for an example of a polar graph) to summarize statistics on mortality during the Crimean War. Looking at her polar graphs of deaths due to combat vs. disease, plotted over many months, it was hard for Parliament to deny that by far the majority of the young English lives being lost in the war with the Russians were due to entirely preventable causes. When Parliament had little choice but to offer up an increase in the budget for sanitation and preventative health care, Nightingale produced equally elegant graphs showing the resulting reductions in mortality.

Given such a fine example as a starting point for the field of graphical displays of information in medicine, one would think that a hundred years later we would enjoy the benefits of far better graphic displays, creative and useful ways of looking at data and seeing the information therein. Unfortunately, however, there has been little progress. Even as recently as 1990, one could turn to the best journals in medical informatics and find a paper published that shows little awareness of a century of use of such diagrams, reporting the polar graph as though it were a new discovery [1].

Graphical displays in medicine tend to be created out of an immediate need to improve usage of information in a particular medical setting, not out of a theoretical program aimed at systematically testing and building upon the contributions of fellow scholars. As a result, when one turns to the literature on display of medical data, there are few if any well grounded principles to follow. There are hardly any crude rules of thumb, much less well codified laws. This means that a medical informaticist called upon to create an interface for some information system can find little or no systematic analysis to build upon. Some might argue that graphical display of data is an art, not a science, and that fundamental laws or theoretical distinctions are simply not possible. Thoughtful examination of a few types of medical data displays, however, will dispel that notion.

The present analysis has as its goal the explication of two principles of data display. It will be argued that these are not mere rules of thumb or ephemeral aspects of graphics, aspects that are of consequence in some settings but are irrelevant in others. The present thesis is that each of these is a fundamental dimension of graphical representation, dividing the world of graphical displays in a meaningful, useful, and theoretically interpretable way. If the analysis is correct, three benefits will result. First, these principles will help us make sense of existing graphic displays, give us a means of categorizing them and understanding why some work and others do not. Second, these two principles can be applied in an engineering procedure, guiding the pragmatic act of creating a data display that makes a complex decision simpler. Third, these two principles, if true, would act as one section of the foundation for the construction of a true theory of graphical representation of data.

INTEGRALITY VS. MEANINGFULNESS

The two fundamental dimensions being proposed here are: *integrality* and *meaningfulness*. The first is a syntactic dimension, the second semantic. Understanding each dimension and how the two dimensions differ from one another is easy if we consider four examples taken from recent medical literature.

Low integrality, low meaning: Line graphs

Surely the most common graphic display of data in medicine is the line graph. Figure 1 [2] shows five medical measurements varying over 25 epochs of time. The measurements here might be five vital signs taken from an ICU flowsheet, the 25 epochs might be 25 hours. Line graph displays aim to make clear not only how one measure varies across the x-axis, but to make apparent any patterns of variation such as when two measures are highly correlated.

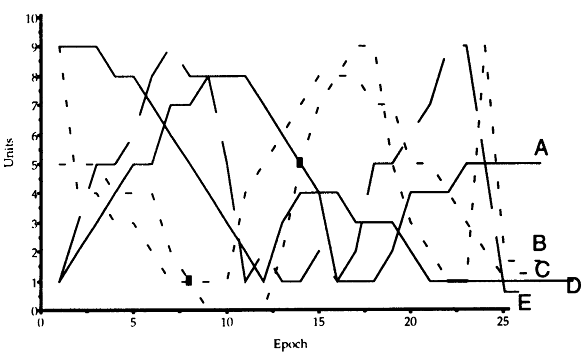

Figure 1. Line graphs attempt to summarize not only variation in a single measure, but configurational changes, correlations among measures.

In this graph, two variables are in fact highly correlated. One of the lines is nothing more than the mirror image of another of the lines; it shows the same data, but in reverse order. The aim of the graph is to make such correlation clear. Does it succeed?

This graph is the starting point for understanding all that is wrong with graphic representation and for understanding the two principles that guide us to better displays. Line graphs are low on both integrality and on meaning. Polar graphs are higher on integrality, although still low on meaning, and studying the contrast between line and polar graphs helps make clear the concept of integrality.

High integrality, low meaning: Polar graphs

Polar graphs are sometimes called star graphs, circular graphs, or spider graphs. No one term is authoritative. Figure 2 shows a simplified version of a polar graph created by Williams [3]. Here, several laboratory tests for one patient are shown by plotting the value of each lab test on a visual scale that has been carefully laid out so that if all the lab tests came back with exactly normal values, the ring that results when we connect the individual lab values would form close to a perfect circle. If this patient's lab values had been abnormally high for one test we would see the ring shape spike outward sharply at one point. If a lab value were unusually low, the ring shape would collapse inward at that point.

The advantage of such a graph over a series of bar graphs of these same test results is that a polar graph forms a shape and some of these shapes may come to be familiar and recognizable much as some constellations of symptoms come to be familiar and recognizable as a syndrome or as the attributes that almost always signal one particular disease.

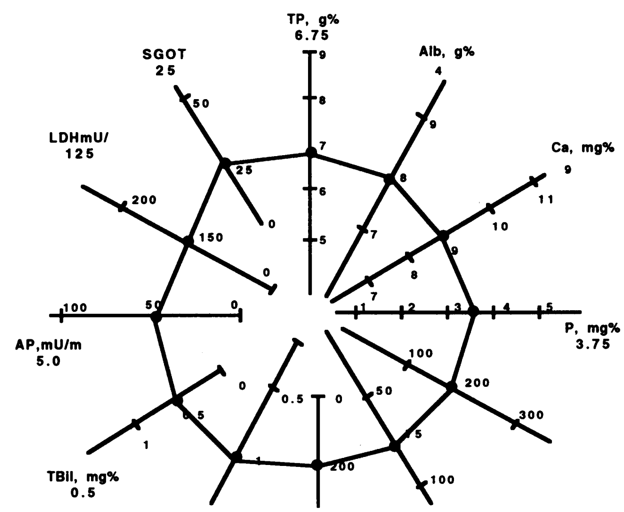

Figure 2. A polar graph representation of one patient's lab tests. By connecting the dots indicating test values, thus forming a ring, a shape is formed that may be recognizable. A shape close to circular signals lab values close to normal. Such a graph is integral to the degree that changing any one value changes some global attribute, such as shape of the ring.

As with line graphs, polar graphs aim to make apparent not only the state of any one measurement, but patterns of covariation among measurements as well. How well they do this has not been rigorously researched (almost all papers on graphic representation in medicine present a graphic method as of obvious value; almost none go on to empirically evaluate the method) but one thing can be said about them on purely formal grounds, without the need for empirical research. They are more integral than line graphs, in a technical sense of integrality.

Integral vs. separable is a theoretical distinction first proposed by Garner [4] , a cognitive psychologist developing a theory of visual perception. He pointed out that it is hard to consider certain stimulus dimensions while ignoring others. For example, it is hard for humans to make judgments of the color hue of a circle while ignoring simultaneous variations in color saturation of that circle. Hue and saturation are thus said to be *integral* dimensions, in the sense that changes in one tend to influence judgments of the other. Judgments of hue, however, are unaffected by variation of the circle's size. Hue and size are thus said to be *separable* dimensions. Garner proposed, and a great deal of empirical research has since confirmed, that integral dimensions are processed quite differently by the human information processing system than are separable ones. Wickens (e.g. [5]) and other researchers have applied the integral vs. separable distinction to data displays, largely in aviation, and are progressing toward a theoretical framework explaining why integral displays are better for some tasks than separable ones.

Polar graphs are, in this technical sense, far more integral than line graphs. The several measurements are combined in such a way that an overall shape emerges. Change any one of the values and a fundamentally different shape results. Line graphs, in contrast, form no shape except in certain special cases (two lines might cross over to form an X, for example). Change any one line out of five and the change might be hard to detect. Cole and Stewart [2] used the term "graphic spaghetti" to describe line graphs with many variables, observing that not only is it difficult to spot any overall configural pattern in a complex line graph, but it can even be difficult to follow any single line in a maze of overlapping lines. Whether or not integrality leads to significantly better information processing is an empirical question (human factors research by Wickens and others suggests that for certain kinds of tasks it does) but it is proposed here as a formal distinction between line graphs and polar graphs, a formal dimension along which any graphic display can be placed, as in Figure 3.

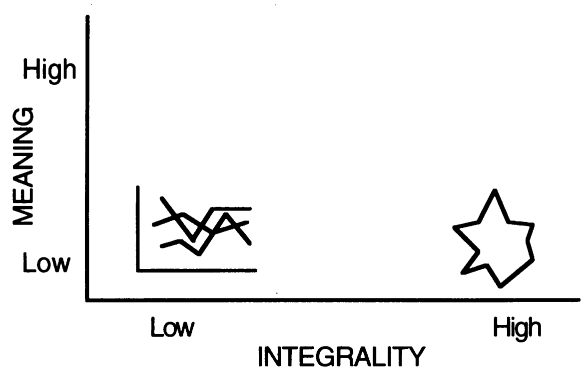

Figure 3. Line graphs and polar graphs differ in integrality but are equally low on meaning.

Low integrality, high meaning Concept graphics.

Figure 3 shows polar graphs as higher than line graphs on the dimension of integrality, but shows both as relatively low on a second scale, labeled *meaning*. Meaningfulness is a very slippery dimension and there are many ways this scale could be applied. For present purposes, let us adopt a restricted usage of the term. The key to where a graphic will score on this dimension lies in how meaningful the mapping is between the real world features we wish to display and the graphic features we use to represent them. If all the graphic features very much "look like" the real world features, then a graph will score high on this scale. If the graphic features do not "look like" the real world features, the graph will score low. Figure 4 shows an example of a graphic in which a great deal of effort was expended to create graphic features that "look like" the real world features they represent.

Figure 4, created by Preiss [6], is an example of what he calls *concept graphics*. The figure attempts to represent some features of a medical concept (in this case appendicitis) by means of graphical elements that are highly reminiscent of the real world features. The figure in the upper right, for example, is intended to look like a human kneeling and expelling something from the head area. The disease feature (symptom) being represented here is vomiting. Beneath the rightmost part of the kneeling stick figure is a graphic element intended to look like a thermometer, with a reference arrow on the left pointing to normal temperature and three gradation marks for three different extremities of elevated temperature. The real world feature being represented here is moderate fever. Other graphic elements are meant to look like pain radiating into the lower right quadrant of the abdomen, elevated white blood count, possible constipation, and of special concern in children and the elderly.

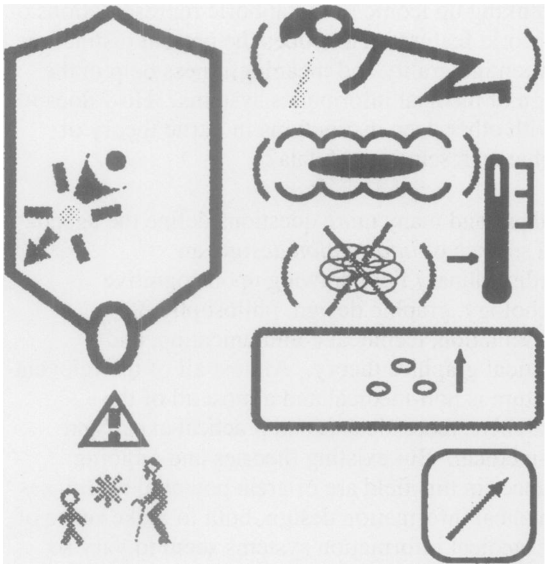

Figure 4. Concept graphics are high in meaning but low in integrality.

Contrast Figure 4 with Figure 1. Lines on line graphs in no way attempt to look like the real world dimensions they represent, with the possible exception of up-ness of a line somehow looking like more-ness in the real world. The concept graphic elements in the appendicitis figure, on the other hand, were painstakingly constructed to look like real world disease features, whether or not they immediately suggest these features. An important point that can only be mentioned in passing is that the test of "looks like" is not "can everyone instantly recognize what the graphic element is trying to signify, even without preliminary explanation". More sensitive tests of "looks like" would be time required for learning and ability to retain over time. For example, Cole and Stewart [7] showed that respiratory therapy experts who could not understand a metaphoric graphical representation of mechanical ventilation data could nonetheless learn the representational scheme in less than five minutes, use it with essentially perfect accuracy, and remember it over two years later even without intervening use or any reason to think they would ever be re-tested.

Concept graphics aim to be highly meaningful, but how integral are they? Many graphic elements are brought together in one space but is any overall shape apparent? Are there emergent features, features that exist when all elements are present and take on certain values, but would disappear if any individual element were to disappear? Would human judgments of variations in any one feature (e.g. height of the dark line within the thermometer element) be more difficult if we simultaneously varied values of some other feature (e.g. changed the number of limbs of the kneeling figure)? Concept graphics appear to be low in integrality.

High integrality, high meaning: Volume rectangles.

Cole has presented several examples of metaphor graphics, including a visual representation of mechanical ventilation of an ICU patient, as in Figure 5 [8].

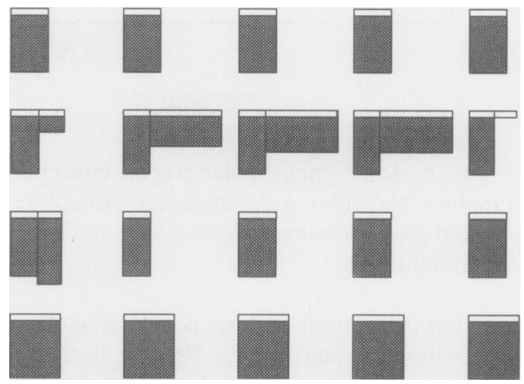

Figure 5 Twenty hours of mechanical ventilation data represented as volume rectangles. Integrated and highly metaphoric.

Here, 20 hours of ventilation data are presented as 20 frames of time: five hours per row, four rows. Each frame has room for two rectangles, as in the first frame of row two. The left rectangle is the ventilator, the right one the patient. Where only one rectangle appears, this is the ventilator alone, with no patient breathing. Each rectangle gets deeper as tidal volume increases and gets wider as the number of breaths per hour increases. Thus in the first frame of row two, the patient has contributed a few, relatively shallow breaths. In the adjacent frame, patient tidal volume (depth) and rate (width) have both improved. Figure 5 thus shows a 20 hour period that began with ventilator alone, saw the patient begin to contribute significantly about halfway through, then saw the patient's contribution fall back to nothing.

CONCLUSIONS

As Figure 6 summarizes, the two dimensions of integrality and meaningfulness are orthogonal. Not all meaningful graphics (e.g. metaphor graphics) are integral and not all integral graphics (e.g. polar graphs) are highly meaningful.

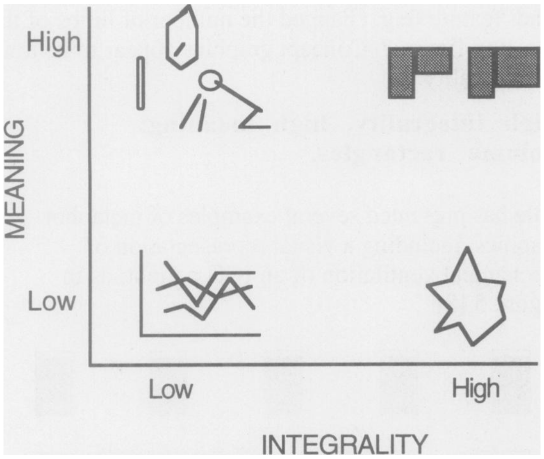

Figure 6. Line graphs, polar graphs, concept graphics, and volume rectangles are examples of high and low integrality, and high and low meaningfulness.

The point of the present analysis is not yet another graphic method for data display. No new displays have been proposed here. Instead, an attempt is made to rise one level higher, to both review what has been done in the past and to offer a pair of orthogonal dimensions that help organize and make sense of previous graphical displays and to suggest two key principles as guides for the creation of new displays. A summary hypothesis can be offered. For tasks in which the desire is to spot patterns in a collection of measures that may be covarying, displays that are further to the right on the x-axis of Figure 3 (more integral) will lead to better pattern detection and displays that are further up on the y-axis (more meaningful) will lead to better understanding of what that pattern means. These (finding a pattern, seeing what it means) are the two human information seeking needs that any graphic seeks to satisfy. Satisfying just one without the other is a success, but a minor one. Satisfying both is difficult but of great value.

Many issues are raised by the present analysis that cannot be addressed in so short a paper. What is the formal definition of "looks like"? What are empirical tests for it? Is there any evidence that graphics more integral and more meaningful are truly better? Better for what? What are the tradeoffs involved in moving up either the integrality or meaningfulness scale? Even if benefits can be empirically demonstrated, surely there must be costs, such as the great difficulty of thinking up iconic or metaphoric representations of real world features. How does the present distinction between integrality and meaningfulness help in the design of medical informatics systems? How does it fit with other deep distinctions in a true theory of graphic representation of data?

All these and many more questions define the agenda for a science of *information design*, an interdisciplinary field drawing upon cognitive psychology, graphic design, philosophy of representation, technical communication, and statistical graphics theory. Almost all of the relevant literature is non-medical and almost all of the researchers, theoreticians, and practical experts are non-medical. But existing theories and ongoing advances in this field are of great potential usefulness in medical information design, both to make sense of why medical information systems seem to vary so much in their usefulness, and to guide the design of new systems.

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